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A Comparative Analysis of the Technical and Economic Feasibility of a Grid-Connected Solar Plant

Mubarak M. Alkahtani[*,1], N. A. M. Kamari[*], M. A. A. M. Zainuri[*], Fathy A. Syam[#]

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ABSTRACT

This study aims to find out how well a PV solar facility possessing 400 MW grid-connected designed in Riyadh city, Saudi Arabia, can meet the demands of an electric load. A dispatch method that forecasts future solar production and electricity consumption was created using the HOMER program. This study investigates the optimal operation of three configurations for a solar plant with three different module sizes. The solar plant was designed using PVsyst and the results were exported to the HOMER program. The proposed system is compared to the base system, which includes load following as well as cycle charging regarding HOMER, is executed utilizing techno-economic optimization and environmental perspectives to obtain the Total Net Present Cost, the minimum Levelized Cost of Energy, and the minimum CO2 emission. The optimization procedures were executed with zero unmet loads and excess energy. The optimization findings illustrated that the suggested system with a large PV module has better energy, economic, and environmental results with the grid purchases (2,347,286,329 kWh/year), LCOE (0.0477 $/kWh), and CO2 emission (1,480,778 ton/year). The optimization procedures were executed with different load levels, and in all cases, the results confirmed that the plant designed with large panels is more economical.

1. INTRODUCTION

The exhaustion of the remaining fossil fuel production and the environmental degradation led by conventional forms of energy make the use of the so-called Renewable Energy Sources (RES) a necessity. Consequently, numerous governments around the world are actively endorsing alternative energy production technologies, including photovoltaic (PV) systems, and public concern about climate change further accelerates their deployment. Among the current RES, PV technology exhibits considerable technological advancement, reliability, and efficiency in electricity generation. In contrast to traditional power generation as well as RES, for example, wind power, the most significant investment in power is presently being directed towards large-scale PV power plants [1]. Photovoltaic grid-connection systems (PVGCSs) feed the entire power output of the solar modules into the electric grid. Investment in their installation is sustained by the high selling price of the produced energy, as well as subsidizing of initial installation cost, and reduced costs of components in recent years aggravate this situation. The PVGCSs are designed, in such cases, to maximize total earnings related to the sale of energy produced by PV to the electric grid. The solar energy potential of the location, the components and topology of the system, and the load significantly influence the performance of a PV power plant connected to the primary electrical grid. The annual power production of the PV plant is meticulously calculated as the aggregate sum of its hourly energy generation throughout the entire calendar year. Furthermore, the existence of this hourly power generation depends primarily on various aspects that include the peak power of the PV module, availability of solar irradiance, efficiency as well as temperature of the PV module, shading effect, the inverter's capacity and topology, the parallel and series connection of the PV modules, the physical layout regarding the other component and the losses that are brought about by maximum power point tracking [2].

Despite the widespread utilization of PVGCS for power generation, a primary challenge in system installation is the sizing of the system. An inadequately sized PVGCS may restrict the electricity fed into the grid or increase the system's cost [3]. Conventional optimization techniques are deterministic, utilizing mathematical formulas to determine global optimal solutions. One advantage is their ability to deliver a definitive answer; yet, it is evident that they struggle to manage numerous interdependent factors inside a complicated, high-dimensional search space. In the initial phases of design and optimizations, conventional

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[*]Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor.

[#]Power Electronics and Energy Conversion Dept., Electronics Research Institute, Cairo, Egypt.

[1]Corresponding author:
Email: p129731@siswa.ukm.edu.my

methods commonly employed numerical, iterative, analytical, and probabilistic analyses, along with graphical techniques [4]. Given the comprehensive range of models for PV modules and inverters available to purchase, another critical issue in sizing would be the optimal choice of such components to enhance the system's performance indicators. To attain this purpose, Artificial Intelligence (AI) was employed as an optimizer in the corresponding sizing algorithms. Optimization algorithms utilizing artificial intelligence are population-centric and are commonly categorized in accordance with swarm intelligence, physical principles, human behavior, and evolutionary concepts [5-8]. The primary rationale for employing artificial intelligence in optimization problems is that classical optimization techniques are inadequate for complex challenges. The effectiveness, speed, flexibility, and doable solutions, along with the aspect of efficiency, make artificial intelligence methods desirable [9-12]. Nevertheless, heuristic approaches also present drawbacks, such as susceptibility to local optima and the necessity for meticulous parameter tuning, prompting recent research into hybrid meta-heuristics and adaptive learning strategies.

Optimal sizing procedures entail the integration of energy resources, the conversion of these resources through appropriate technologies, and the storage of energy to mitigate waste and system inadequacies economically, while ensuring minimum acceptable security to fulfil load demands without compromising environmental integrity. Consequently, the criteria for optimizations are economic, dependable, and environmental, as demonstrated in the subsequent steps [13]. A few review studies on grid-connected PV systems addressing optimization, design, and problems have been published. Consequently, there is an absence of discourse regarding design optimization concerning grid-connected PV systems. Here, [14] investigated the technical as well as economic parameters of grid-connected PV systems. Consequently, various research studies are perpetually undertaken to optimize PV power plants, encompassing the arrangement of components within the installation site, cabling, inverter topology, tilt angle of PV modules, quantity of PV modules and inverters, as well as shading effects [15]. Before commencing the plan, it is essential to simulate the energy infrastructure for informed decision-making as well as pre-feasibility assessment. Numerous commercial as well as free software have been produced to analyse the integration of the renewable systems. The leading ones are used by scholars, namely RETScreen and HOMER, with 200,000 and 28,000 installations, respectively [16].

In India, the performance of a 5 MW solar power plant was studied. The results revealed an energy payback period of 6.49 years, an adjusted cost of electricity of 0.23 Indian Rupees/kWh at a 5% interest rate, and a 30-year lifespan. The power output factor (EPF) and lifecycle conversion efficiency (LCCE) were 3.84% and 1.28%, respectively. The photovoltaic solar power plant significantly contributes to reducing CO2 emissions, by approximately 16,383.54 tons/year, thus contributing to achieving carbon neutrality [17]. The technical and economic feasibility of a 200 MW grid-connected floating solar power plant was improved using PVsyst software. One hundred system configurations were simulated, varying the tilt angles and row spacing, to evaluate power output, performance ratio, and financial viability. The optimal configuration a 22° tilt angle and 0.8 m spacing produces 399.8 GWh per annum, representing 83.21% performance. Economic indicators confirm the project's strong viability, with a levelized electricity cost of US$0.0433/kWh and a payback period of 5.81 years [18]. The effect of tilt angle on the electricity production of a solar power plant was studied in [19] By evaluating energy production at various panel tilt angles ranging from 0 to 26°C, the ideal tilt for the solar PV system was examined. Due to maximum sun radiation, the highest energy generation was discovered at 15 degrees. A detailed analysis was conducted of the performance of photovoltaic power plant with three different configurations, including a fixed tilt tracking system, an adjustable tracking system, and a single-axis horizontal tracking system at a single site. An increase in energy production of 0.06% was observed in the components of the photovoltaic solar power plant with an adjustable optimal tilt, compared to those with a fixed tilt [20-21]. In small-scale solar power systems, we may need to add batteries to store energy to meet load requirements and increase the economic feasibility of the system [22].

The study is organized as follows: Section “Research literature using Homer” presents some recent researches in optimization of the PV grid connected system using the HOMER program. Section “Methodology” describes the methodology of the system optimization procedures includes the data inputs, load specification, and software. Section “Design specification and simulation assumptions” describes the system modeling. Section “Electricity simulation results” introduces the electrical results and discussion. Section “Economic results” introduces the economic results and discussion. Section “Sensitivity” presents the electrical and economic results with different loads. Section “Conclusion and future work” includes the conclusion of this study and the work in the future to complete the study.

2. RESEARCH LITERATURE USING HOMER

A techno-economic analysis (TEA) study concerning the PVGCS plant was performed utilizing a simulation model with the Hybrid Optimization Model for Electric Renewable Sources (HOMER Pro) software. HOMER is widely recognized as a powerful micro-grid tool, and the Pro edition extends its capability to large grid-interactive PV plants. The optimal PV array as well as inverter sizes with respect to a grid-connected PV system were analyzed. To achieve appropriate sizing, factors such as net present cost (NPC), proportion of renewable electricity, unmet load, surplus electricity, as well as percentage of carbon dioxide (CO_2) emissions are taken into account. Furthermore, using the sensitivity and risk-analysis module inside HOMER, the study examined

discount rates from 6 % to 12 % and projected PV-module price declines of up to 30 % to verify financial robustness. An optimal outcome, characterized by 0 % surplus electricity and unmet load, for electricity provision in Makkah, Saudi Arabia, is accomplished with a PV-to-inverter size ratio of 1 while minimizing CO_2 emissions. Nonetheless, the inverter size may be lessened to 68% of the PV nominal power to lower inverter cost, thereby diminishing the system's TNPC [23].

A feasibility study was conducted with regard to a grid-connected solar PV system for electricity generation at a chosen site in northern Nigeria employing the HOMER energy-optimization program. The technical as well as economic performance of an 80 kW grid-connected PV system was evaluated. In the base-case scenario, with a solar PV cost of \$2400 kW^{-1} as well as an average global solar radiation of 6.0 kWh m^{-2} day^{-1}, the system generates 331,536 kWh annually, with solar PV accounting for 40.4 % of the total supply. The levelized cost of energy (LCOE) is \$0.103 kWh^{-1}, and the investment gains a simple payback period of 8.2 years in total with an Internal Rate of Return (IRR) of 13.5 % under the stated assumptions [24].

In [25], methods for techno-economic optimization as well as system-performance analysis were proposed. The analysis was executed for an established PVGCS utilising one-year plant-logger data (2018), having a model-based MATLAB/Simulink simulation as well as HOMER software. Simulation results indicate that an optimized PV array of 5 kWp is recommended, yielding an €5770 NPC as well as a cost of energy (COE) of €0.087 kWh^{-1}, whereas the original 10 kWp installation has an NPC of €6047 and a COE of €0.098 kWh^{-1}.

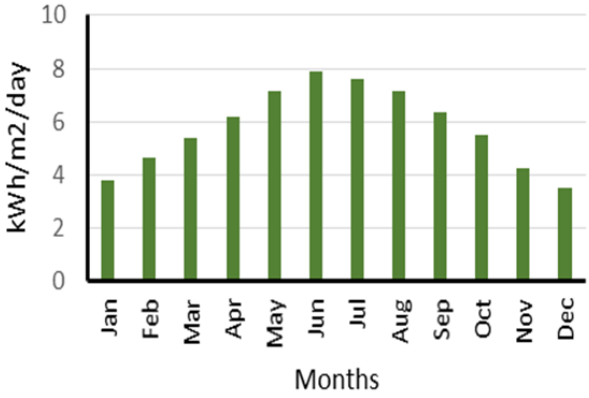
Finally, the research conducts a techno-feasibility experiment concerning a 400 MW grid-connected PV system located in Riyadh, Saudi Arabia. This investigation forms part of a broader economic assessment of large-scale PV plants that explicitly considers the recycling of end-of-life solar modules. HOMER is used to optimize the levelized cost of energy (LCOE), total net present cost (TNPC), as well as CO_2 mitigation while respecting grid-demand constraints. For the 400 MW case, a real discount rate of 7 %, a 25-year project lifetime, as well as an annual degradation factor of 0.5 % have been assumed to mirror current utility-scale practice. In addition to the economic metrics, the study incorporates detailed operation and maintenance (O&M) expenditures, scheduled inverter replacement in year 12, and potential revenue from newly announced green-certificate incentives. The differentiates in this research lies in the comparative economic feasibility study of solar power plants using different sizes of solar panels as part of an integrated study of solar panel recycling and the impact of panel size on recycling yield, thus contributing to reducing energy costs.

3. METHODOLOGY

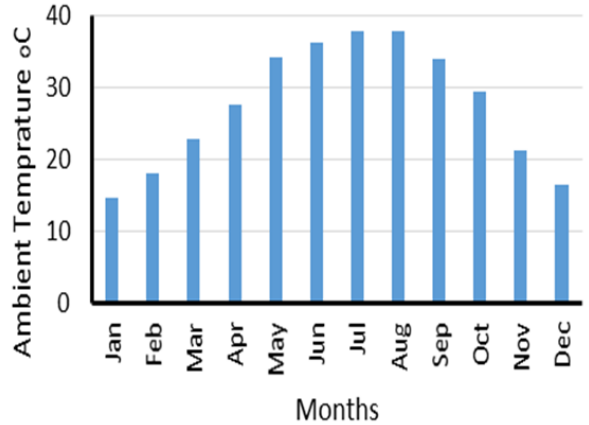
The solar plant was designed using PVSYST software for three different sizes of solar panels: 580Wp, 330Wp, and 255Wp [26]. The results output file from the PVSYST program was relied upon and exported to the HOMER program to be one of the most important inputs for the optimization process. The system's components, size, and input data will be explained in the following sections.

3.1. Meteorological Data

A careful analysis of the selected site is critical to designing an optimal PV system. Saudi Arabia is in southwest Asia. Riyadh is the city with the largest population in the Kingdom by area and a major political centre, located at 24.69° N and 46.69° E at an elevation of about 612 m. When considering solar radiation, the median global horizontal irradiance (GHI) concerning Riyadh is approximately 2,200 kWh m^{-2} $year^{-1}$, ranking it among the sunniest capitals worldwide. In this work, synthetic hourly solar irradiance obtained by HOMER from monthly average values was utilized, from NASA's Surface Meteorology as the source [27]. The energy output of a PV system is established by ambient temperature as well as solar radiation; the mean annual air temperature is nearly 27 °C. Figure 1 shows the mean monthly solar radiation and temperature levels in Riyadh. Solar radiation levels vary with the seasons and naturally increase during the summer months with increased periods of sunshine. Note that the median solar radiation in Riyadh is approximately 5.8 $kWh/m^2/day$.



(a) Solar Radiation



(b) Ambient Temperature

Fig. 1. Solar radiation as well as the ambient temperature of the selected location.

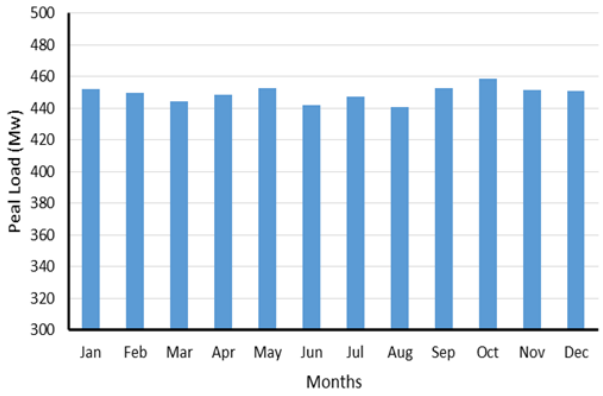


Fig. 2. The monthly distribution concerning the load profile.

3.2. Load Profile

Using measurements of the maximum consumption values for various loads, the electrical load profile for the area under research was determined. Regarding the load data collected, the maximum primary load demand is 3204 GWh/year, with a 468 MW peak load value and 877.7MWh/day. According to the data for the load profile under study, Figure 2 shows the average load profile data.

3.3 Simulation Software

The HOMER Pro software, established by the United States National Renewable Energy Laboratory (NREL), is an advanced tool for the design, analysis, and planning of both grid-connected and stand-alone power systems. It facilitates the determination of optimal component sizes through comprehensive TEA. HOMER evaluates grid-connected PV systems by modelling life-cycle operational performance and cost behaviour over the entire project horizon. An iterative optimization engine simulates thousands of possible dispatch strategies, then ranks each configuration according to renewable fraction, net present cost, and predicted emissions. The simulation requires detailed inputs covering initial capital, O&M, replacement costs, site-specific load profiles, and meteorological resources [28], [29]. Figure 3 illustrates the architectural diagram of the HOMER Pro simulation method.

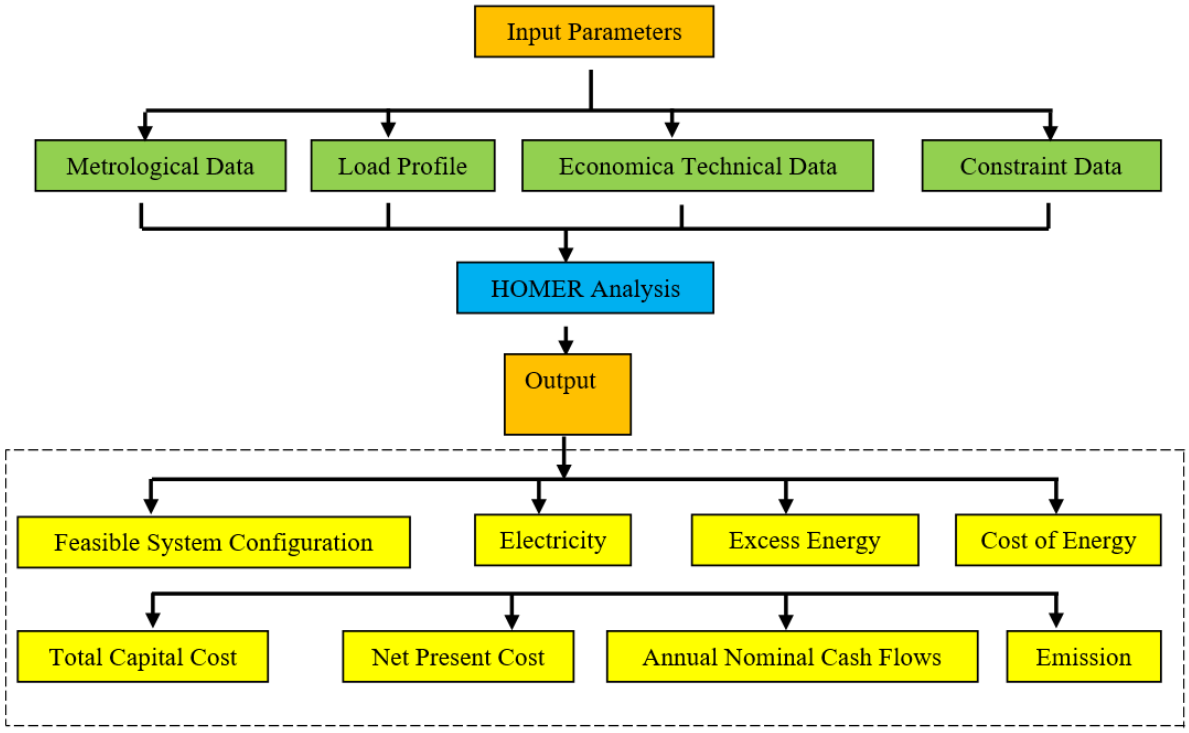


Fig.3. Optimization process framework in the HOMER software

4. DESIGN SPECIFICATION AND SIMULATION ASSUMPTIONS

To complete the simulation process, all necessary assumptions must be specified as inputs to the Homer program, such as the system components in terms of electrical power capacity, the number of solar modules and the capacity of each module, and the number and capacity of inverters used. The study site, solar radiation values in the selected area, and the load fed by the proposed system and the grid must also be specified, as explained in Sections 3.1 and 3.2. In order to compare the proposed system with the base system (grid) and to clarify the economic feasibility of the proposed system, the cost of energy produced from the grid must be determined. All these assumptions will be explained in the following sections.

4.1 System modelling

The PVGCS was simulated with HOMER software and consists of a 400 MWp PV field coupled to a 275 kW grid-connected inverter rated at 98 % peak efficiency. The overall configuration of the PV array, utility grid, load, and bidirectional converter is modelled by assigning the actual electrical ratings and control parameters used on site, including string voltage limits,

maximum-power-point-tracking range, as well as unity-power-factor operation. Monocrystalline modules are arranged in south-facing strings tilted at 24° to capture the city's optimum annual irradiance. Figure 4 depicts the schematic illustration of the entire system concerning PVGCS.

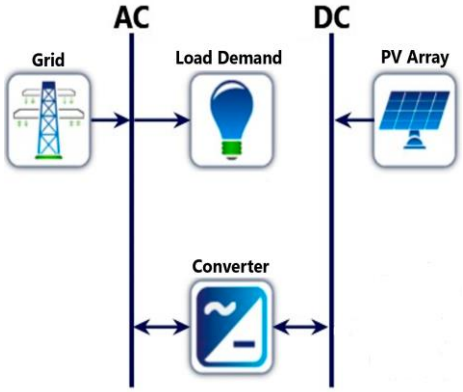


Fig. 4. Schematic diagram about the PVGCS system.

4.2 PV Arrays

The solar power plant is designed for direct interconnection with the utility grid. Rating data are adopted from a 580 Wp monocrystalline module installed at a site in Riyadh, Saudi Arabia. Accordingly, 689,650 of these 144-cell modules are required to reach the 400 MWp array capacity. The selected module delivers 21.3 % certified efficiency under standard test conditions and exhibits a temperature coefficient of −0.35 % / °C, helping to preserve output in Riyadh's high ambient temperatures. Optimal solar-radiation absorption mandates mounting the panels at a fixed tilt 30°; therefore, each string is oriented due south at an angle approximately equivalent to the site's latitude to optimize yearly energy yield.

4.3 Converter

A converter refers to a power-electronic device that transfers electrical energy from direct current (DC) to alternating current (AC) during inversion as well as from AC to DC during rectification. Within HOMER, both solid-state and rotary converters can be represented. The inverter capacity, described as the maximum AC power that may be produced from DC, is entered by the user. Meanwhile, the rectifier capacity is established as a percentage of that value and therefore is not an independent decision variable. HOMER treats inverter and rectifier operation as continuous, assuming the device can sustain the specified load indefinitely and operate in parallel with other AC sources, such as the grid. In grid-connected configurations, the converter also synchronises voltage phase and frequency with the utility, ensuring seamless bidirectional power exchange and preventing harmonic distortion within allowable standards. The fundamental parameters required by the model are inversion and rectification efficiencies, which HOMER assumes remain constant throughout the simulation horizon [30].

4.4 Grid

Given that the PV system is linked to the utility network and combined with other generation assets, the grid capital expenditure is limited to the one-time interconnection fee; otherwise, HOMER assigns the grid a capital cost of $0. In the software, the grid replacement cost is always zero because the utility is treated as an "infinite" source and sink that does not age out within the project horizon. Grid O&M cost is measured as the yearly expense of purchasing electricity, including both energy and demand charges, minus any revenue earned from selling excess electricity back to the utility. For a grid-connected PV system, the model also covers the standby fee that ensures continuous availability. Because the PVGCS operates in conjunction with the grid, overall system reliability is increased, and the local load is expected to receive electricity whenever required. In this study, the retail energy price was set in HOMER at $0.06 kWh^{-1}, and that single value is applied uniformly across all hours of the simulation [31].

Photovoltaic panels generally exhibit optimal performance for a duration of 25 years, after which their production progressively deteriorates. The simulation established the average price of a photovoltaic panel, inclusive of installation costs, as $750 per kilowatt. Normal maintenance is necessary during operation; nevertheless, there are no operational costs. In relation to the capital and installation expenses, the operation and maintenance (O&M) costs are quite minor. The operational and maintenance cost for each kW of photovoltaic array was estimated at $10 per year. The O&M cost encompasses the expenses associated with the removal of dirt and dust from the PV panel and the correction of the PV panel's orientation [32].

5. ELECTRICITY SIMULATION RESULTS

This part introduces the measurement findings concerning the TEA as well as the maximization of grid-connected solar PV systems utilizing the HOMER grid. Consequently, the optimization results are presented initially, followed by the TEA results, together with a brief overview of the potential emissions reduction. Developing a new dispatch methodology using HOMER software to forecast solar energy production and projected electricity consumption. The HOMER predictive approach relies on 48-hour forecasts to optimize system operation, potentially reducing operating costs compared to alternative dispatch strategies. It also predicts future energy requirements and solar accessibility, facilitating optimized battery management and improving solar self-consumption. This dispatch approach aims to emulate contemporary systems that use forecasting to optimize performance. The system has a two-day forecast, allowing it to predict future demand and renewable energy generation.

5.1 Optimization Results

The optimization results for the solar plant located in Riyadh city, Saudi Arabia (24.69 N, 46.69 E) are presented here. Within HOMER, the grid-search algorithm evaluates the life-cycle cost of numerous

candidate configurations and selects the design that minimises the COE, LCOE, and annual CO_2 emissions while simultaneously meeting load-reliability constraints. This iterative procedure also generates sensitivity curves that reveal how variations in fuel price or discount rate might alter the preferred solution. The system's optimal results, sorted by HOMER, are summarised in Table 1. The reported metrics include component sizes, mean electrical output, capacity factor, dedicated converter rating, and the percentage share of renewable contribution.

Table 1. The system's optimal results are sorted by HOMER.

Quantity	Value			Units
	580 Wp	330 Wp	255 Wp	
Mean Output Power	98,257	94,256	92,593	Kw
Mean Output Energy	2,358,179	2,262,148	2,222,239	Kwh/day
Capacity Factor	25.5	26.9	26.5	%
Total Production	860,735,240	825,683,852	811,117,364	kWh/yr
Hours of Operation	4,260	4,275	4,247	hrs/yr

Table 2. The production and consumption summary sorted by HOMER.

Quantity	Value		
	580 Wp	330 Wp	255 Wp
Generic flat plate PV (Kwh/year)	860,735,240	825,683,852	811,117,364
Grid Purchases (kWh/year)	2,347,286,329	2,379,525,300	2,393,635,508
The total generation energy	3,208,021,569	3,205,209,152	3,204,752,872
AC Primary Load (kWh/year)	3,203,739,146	3,203,739,146	3,203,739,146
Grid Sales (kWh/year)	4,282,423	1,470,006	1,013,727
The total consumption	3,208,021,569	3,205,209,152	3,204,752,872

The results in Table 1 show that a power plant designed with high-power panels produces a greater amount of electrical energy than others, due to the reduced losses resulting from fewer conductors.

5.2 Electricity Generation and Consumption Results

The optimal system for a 580 Wp solar panel generates 860,735,240 kWh per year from solar PV (26.8 %) and purchases 2,347,286,329 kWh (73.2 %) from the grid, as illustrated in Table 2. Total power consumption equals 3,203,739,146kWh, whereas grid sales reach 4,282,423kWh per year. The total generation energy is 3,208,021,569 kWh per year, while the total consumption is 3,208,021,569 kWh per year. The generation and consumption of energy are the same value; therefore, there are no unmet loads and excess energy. The results show that the solar station using large panels produces more energy due to lower losses. The ratio of energy generation using 330Wp and 255Wp is 25.8 % and 25.3 % respectively. The slight difference in the percentage of solar energy produced between the three panels is due to the large size of the load.

Naturally, less energy will be purchased from the grid when using large panels due to the increased energy produced by the power plant. In Figure 5, the monthly PV and grid electric productivity is provided for the system with 580 Wp. Figure 6 shows the time series chart for the PV system, grid purchases, and total electric load served.

It is shown from Figure 6 that the total energy produced by the solar system and the energy purchased from the grid equals the total load energy, which means that there is no excess energy or unmet load.

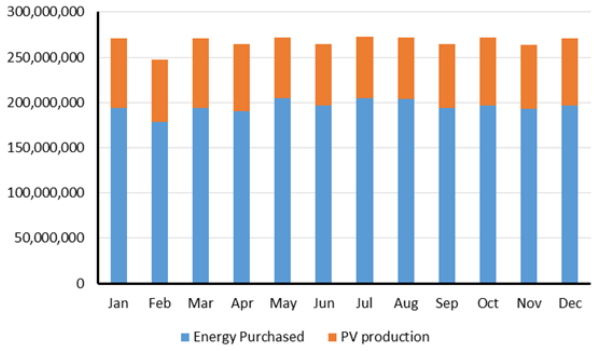


Fig.5. Monthly electric production regarding solar PV and the grid for 580 Wp.

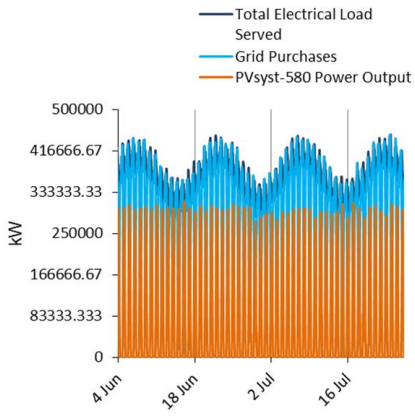


Fig.6. The time series chart for the PV system, grid purchases, and total electric load served.

6. ECONOMIC EVALUATION

The TEA regarding an engineering system is calculated using some of the economic data. Such data involves the nominal interest rate, the anticipated inflation rate, and the project life. The rate regarding annual real interest is recently referred to as the simple interest rate or (real interest rate), and it is an input in HOMER. It resembles a rate that is charged as a discount in the process of transforming one-time costs to annual costs. This is the system's average cost/kWh of usable electrical energy, which is termed the levelised COE by HOMER [33].

$$\mathrm{LCOE} = \frac{C_{ann}}{E_{Ac} + E_{DC} + E_{grid}} \quad (1)$$

HOMER uses the total annualized cost of generating electricity (total annualized cost reduced by the cost of feeding the load) and divides it by the total amount of electrical energy that can be used to find a COE. Total annualized cost will be the addition of all the annualized costs of all system components, together with other recurring charges. These annualized values are calculated by converting initial capital and future replacement expenses into equivalent uniform annual costs using the selected discount rate and project lifetime. This metric is important since HOMER utilizes it to measure both the levelised COE as well as the TNPC of the project. The TNPC of a system is the present value of the total spending of a system over the system's lifetime, less the present value of the total income of a system over the same time range. Costs, which include replacement expenses, capital outlays, O&M charges, fuel costs, pollution penalties, as well as the purchase of electricity from the grid, whereas revenues arise primarily from electricity sales back to the utility.

$$C_{NPC} = \frac{C_{ann}}{CRF} \quad (2)$$

This study indicates that the system's lifespan is 25 years, and the capital recovery factor (CRF) is a metric employed to evaluate an yearly present value, represented by a series of uniform annual cash flows. Hence, the equation regarding the CRF is as follows:

$$\mathrm{CRF} = \frac{i(i+1)^N}{(i+`)^N - 1} \quad (3)$$

There are two sources of revenue, for example, salvage value as well as grid sales income. We give the value with regard to a power system component that still works when the project is completed within its stipulated time, the name of the salvage value. Note that HOMER uses this equation to identify the value concerning each component at the end of the life cycle of the project.

$$\mathrm{S} = C_r \frac{R_r}{R_c} \quad (4)$$

The IRR measured the discount rate where the net present cost of the optimized system equals that of the reference case. HOMER determines this value by iteratively adjusting the discount rate until the present value of the differential cash-flow series becomes zero, thereby identifying the project's break-even financing point. A higher IRR implies a more economically attractive investment relative to the benchmark configuration.

The simple payback calculates the years it will take for the amount of cash flow generated by the difference between the optimized and the reference system to turn negative to positive. Put differently, it represents the time needed to recoup the incremental capital outlay, disregarding discounting and residual value effects.

6.1 Economic Results

The economic performance of the renewable energy system was evaluated through a comprehensive TEA. When estimating economic benefits, operational expenses, initial investment, and scheduled replacement costs must all be considered, thereby capturing every cash flow that occurs during the project lifetime. Within HOMER's grid model, the TNPC was taken as the primary decision criterion for choosing the most advantageous configuration. By comparing TNPC values across alternative component sizes, the optimizer systematically identifies the least-cost solution. Where the purpose is to encourage solar deployment or to compare projects of dissimilar scale, the LCOE serves as a complementary indicator.

6.2 Compare Economics

In HOMER, the "base system" serves as a benchmark for evaluating different proposed renewable energy systems. It is the standard by which the economics of proposed alternative systems are evaluated. HOMER uses this base system approach to calculate metrics such as net present cost, levelized cost of energy, and payback period to determine the most economical system design. HOMER employs the base system to assess the economic advantages of alternative proposed systems. For instance, it can quantify the savings of a renewable energy system in comparison to a base system such as a diesel generator system or grid.

The complete economic comparison of the base (grid) as well as proposed (optimized) systems is discussed in Table 3. The IRR represents the discount rate where the reference case as well as the optimized system yield identical net present costs; in this study, the IRR ranges from 15 % to 17 %. Because this value is greater than the real discount rate employed in HOMER, the project is considered financially attractive relative to the benchmark. By discounting future cash flows as well as acknowledging the money time value, the discounted payback period shows how many years are required to regain the initial outlay; here it is 5.51, 5.75, and 5.85 years for the 580, 330, and 255 panels, respectively. The simple payback, which ignores discounting and therefore provides a more conservative view, equals 5.88, 6.15, and 6.27 years for the 580, 330, and 255 panels, respectively. Simple payback is obtained by splitting the incremental capital cost by the corresponding annual savings [34].

Table 3. Compare the economics between the base and proposed systems.

Economic Parameters	Base system	Proposed system		
		580 Wp	330 Wp	255 Wp
Net Present Cost	$6.28B	$5.00B	$5.07B	$5.10B
CAPEX	$0.00	$280M	$280M	$280M
OPEX	$192M	$145M	$147M	$148M
LCOE (per kWh)	$0.0600	$0.0477	$0.0484	$0.0487
CO2 Emitted (ton/yr)	2,024,763	1,480,778	1,502,931	1,512,137
IRR (%)	-	16.7	15.9	15.5
Discounted payback (yr)	-	5.51	5.75	5.85
Simple payback (yr)	-	5.88	6.15	6.27

By comparing the three proposed systems for designing a solar plant using different sizes of solar panels, it becomes clear that the plant designed using large solar panels 580Wp gives better economic performance. Figure 7 shows the comparison between the economic performance parameters of the three proposed systems. All economic performance parameters indicate that a solar plant designed using large-sized solar panels provides better performance. The LCOE, NPC, and simple payback period are lower when using 580 panels instead of 330 or 255. The main reason for this is the increased amount of energy produced by the solar plant in the case of using a 580 Wp solar panel instead of 330 or 255. The minimum LCOE is $0.0477 per kWh meanwhile, the price of electricity in Saudi Arabia ranges from $0.48 to $0.08 per kWh.

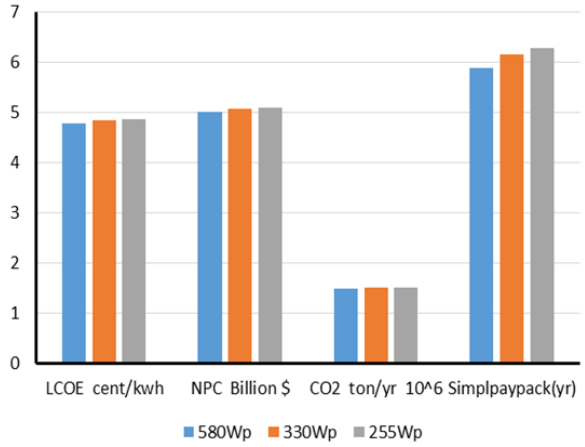


Fig. 7. The comparison between the economic performance parameters of the three proposed systems.

The emission reduction is calculated based on the potential energy that is actually produced by the aim concerning the renewable energy system to substitute the energy of fossil fuels. Carbon emissions represent up to 90% of total emissions, and therefore they were used to estimate and compare the volume of emissions. This is also operationalized as emissions/unit of energy consumed. Compared to the base system, the proposed system emits 27% less carbon dioxide. The amount of carbon emissions seems large, but compared to the size of the solar plant under study, which has a capacity of 400 MW, it is an acceptable number due to the large size of the solar plant.

6.3 Cash Flow

The cash-flow profiles concerning the optimal configuration produced by HOMER are displayed in Figure 8 for the base and the 580, 330, 255 Wp proposed systems respectively.

The original capital cost of a component relates to the total installed investment at time zero and covers the PV generators, single-axis trackers, grid-connection hardware, and power converters. O&M cost denotes the recurring expenditure necessary to keep each component functioning throughout its service life [35]; the system-wide O&M cost is the sum of the individual items. As illustrated in Figure 8, the annual O&M cash flows appear as a negative bar of $144,580,200, signaling continuous outgoings.

In the cash flow, the solar plant breaks even in 5.88 years (intersection between red line and blue line) of production, where the cash flow is positive. The value concerning the suggested system is higher compared to the base system.

7. SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to evaluate the impact of varying input parameters on system performance and to identify the most influential factors. In this study, the parameters examined are load consumption and solar irradiation for the optimized grid-connected PV system. The results of this analysis indicate that the NPC remains comparable when the daily load demand varies by ± 10 % while keeping solar irradiation constant, as shown in Table 4.

The economic results and the assessment of the PV grid-connected system are compared with similar studies in Saudi Arabia. The results are largely verified when compared to studies conducted under the same geographical and environmental conditions [36]. It was found that the renewable fraction has a clear impact on the cost of producing a kilowatt, as a study in Saudi Arabia showed that the production cost ranged between $0.047/kwh and $0.057/kWh [37]. In this research the cost of energy is ranged from $0.046/kwh to $0.0498/kwh.

According to the results shown in the table, increasing the load leads to an increase in the economic performance parameters of each solar plant. But the economic performance improves with the large-panel solar plant for the same load. The LCOE always decreases with the decrease in load, and the NPC always

increases with the increase in load. For the same load, the LCOE and NPC are lower with the use of larger solar panels. The PV penetration ratio is a maximum value of 29.7 % with a large panel of 580 Wp and a minimum load. Also, the PV penetration ratio is a minimum value of 23 % with a small panel of 255Wp and a maximum load. These results are logical because the solar plant with a large panel has fewer losses due to the reduced size of the connecting cables, resulting in greater electricity production.

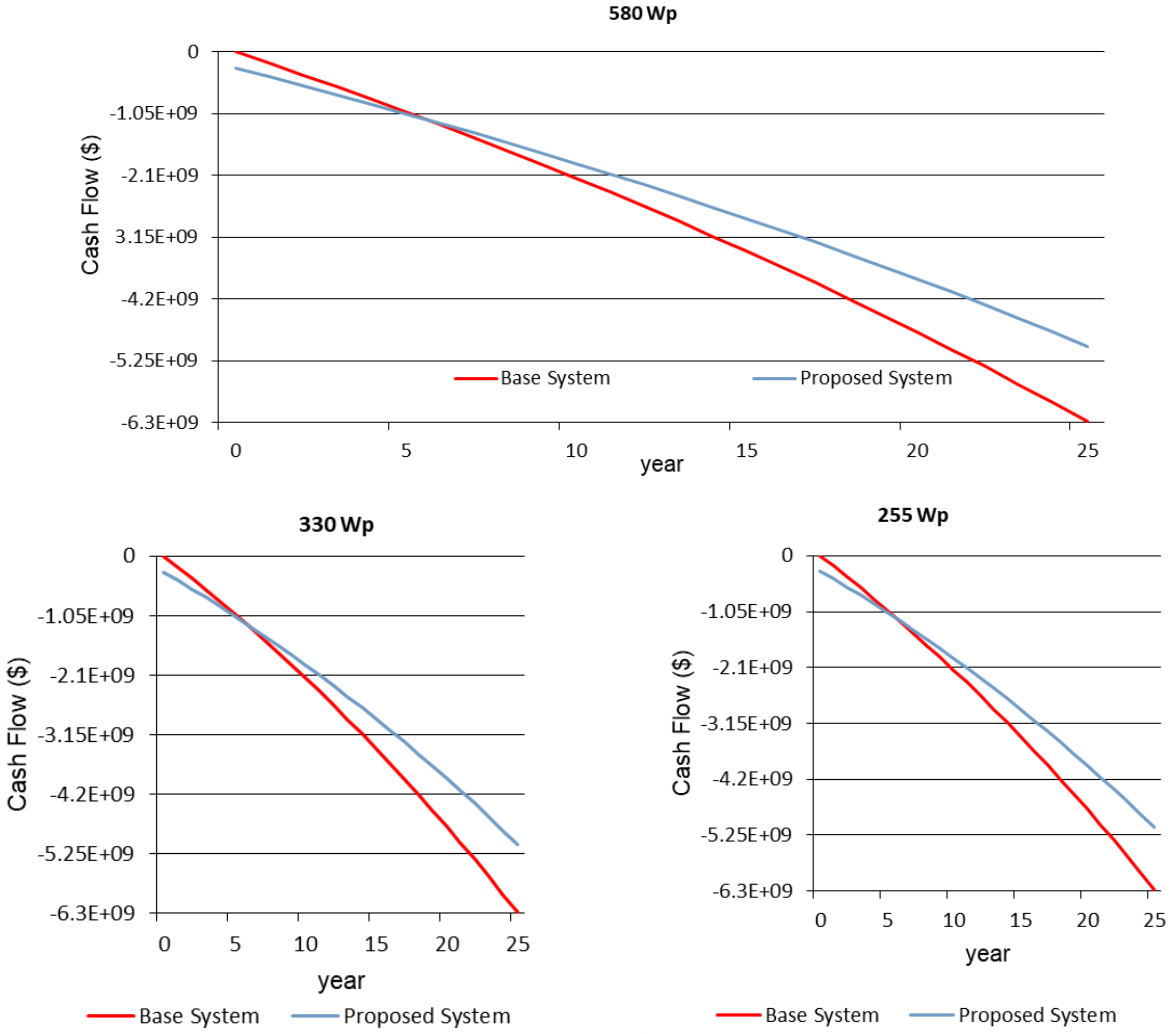


Fig. 8. Cumulative discounted cash flows for the three proposed systems.

Table 4. Comparison of economic performance parameters with load change for the proposed systems.

Economic Parameters	Proposed system								
	580 Wp			330 Wp			255 Wp		
	-10%	Normal load	+10%	-10%	Normal load	+10%	-10%	Normal load	+10%
Net Present Cost (B$)	4.38	5.00	5.63	4.44	5.07	5.7	4.47	5.10	5.73
CAPEX (M$)	280	280	280	280	280	280	280	280	280
OPEX (M$)	125	145	164	127	147	166	128	148	167
LCOE ($/kWh)	0.046	0.0477	0.0489	0.047	0.0484	0.0495	0.0474	0.0487	0.0498
PV penetration ratio %	29.7	26.8	24.4	28.5	25.8	23.4	28.1	25.3	23

5. CONCLUSION AND FUTURE WORK

The work presented in this article represents one of the early attempts in a developing country like Saudi Arabia to implement HOMER software in a 400 MW solar power plant, which is also linked to the utility grid. The economic desirability of a grid-connected PV system has been studied. Three solar system configurations were designed for three different solar panel sizes using a PVSYST program, and the output file was exported to the HOMER program to represent the primary source of input data. The load profile has been considered to optimize the system with a 468 MW peak load. The results showed a clear difference in the energy produced by the solar system and exchanged with the grid. The

LCOE and CO_2 emissions have been considered to optimise the PV grid-connected system. The optimization results show that the solar plant designed using large panels gives better economic performance in terms of NPC, LCOE, and carbon emissions. The system with 580 Wp has a minimum LCOE equal to 0.0477 $/kWh, while the other systems have LCOE equal to 0.0484 and 0.0487 $/kWh. From an environmental point of view, the solar plant with large panels reduces emissions by 27 %, producing 1,480,778 t year^{-1} of CO_2, while the base system emits 2,024,763 t year^{-1}. Cash-flow analysis shows a discounted payback of 5.51 years within a 25-year project lifetime and a simple payback of 5.88 years for a large panel. The change in load, whether increasing or decreasing, does not affect the conclusion result, which is that the system designed with large panels is more economical. Future work will investigate coupling the plant with utility-scale battery storage, perform a cradle-to-grave life-cycle assessment, and quantify the economic benefits of large-scale panel-recycling schemes under emerging policy incentives. The results of the present economic feasibility study will therefore provide a solid foundation for forthcoming research into recycling the 689,650, 580 Wp solar panels installed in the grid-connected plant.

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